

THE YOUNG'S MODULUS DEPENDENCE OF THE PLASTIC STRAIN

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Abstract. *The advanced high strength steel (AHSS) has become an alternative for weight saving and increasing of the structural/crash/safety performance of the automotives components. However, the substitution of conventional steels for AHSS implicates in new challenges in the planning of the forming process and in the tool project. The springback is the largest problem to be solved; therefore its prediction through Finite Element Method (FEM) doesn't present good results due to difficulty to describe the behavior of those steels during the plastic strain. The Bauschinger effect and the Young's modulus variation are pointed as the two factors of larger influence in the deviations found in the computer simulation. This work aims the study of the Young's modulus variation with the pre-strain for the TRIP600 steel. The results showed a decrease of the Young's modulus with the increase of the submitted strain. The nanoidentation method proved to be a good approach for an accurate Young's modulus measurements. The expectation is to use this data as input in the simulations for a better response in modeling.*

Keywords: *Young's modulus, advanced high strength steel (AHSS), sheet forming, springback*

1. INTRODUCTION

To save fuel by reducing the weight and increase the structural performance, security and resistance to impact, are currently the main concerns of the automotive industry. One of the best ways to achieve these goals has been the use of advanced high strength steels (AHSS) such as the Dual Phase (DP), Transformation Induced plasticity (TRIP) and Complex Phase (CP) among others. These steels have improved formability and much higher resistance than the conventional steels. With these steels is possible to achieve similar performance using thinner thicknesses.

The industrial application of advanced steels introduces new issues to be thoroughly investigated as the impact on design, technological feasibility, development time, trial and error, time-to-market (TTM) and on the investment (Placid *et al.*, 2008).

The springback is a major problem related to mass production of AHSS components. The springback is the result of an elastic recovery of internal stresses after the tool removal, causing a change in the final form of the component. It is not a new problem, but has shown a bigger concern when compared to conventional steels.

A computer simulation by Finite Element Methods (FEM) has been widely used in industrial applications, in design and helping on the forming processes evaluation. It helps to reduce time and tool developing costs (ANDERSSON, 2005). However, the FEM method is only effective for predicting the springback behavior in conventional steels, and has not shown satisfactory results in predicting AHSS springback (ASGARI et. Al, 2007).

The difficulty in prediction of springback in AHSS by MEF is attributed to the difficulty of a correct mechanical characterization behavior of the materials during plastic strain. According Placid et al (2008), several non-linear phenomena arising from micro structural changes during plastic strain are not well described by conventional constitutive equations and its approximations. Two phenomena in particular are pointed out as the main cause of non-linear behavior of these steels; the Bauschinger effect and the Young's modulus variation during plastic strain.

The complete understanding of these phenomena is essential to increase the accuracy of the FEM. Placid et al (2008) suggest two lines of research, (i) implement testing methods to identify the experimental parameters involved in the constitutive equations and (ii) implement constitutive equations that can describe these phenomena effectively.

In the 1990s Morestin and Boivin (1996) conducted studies with conventional steels in order to understand the evolution of Young modulus during plastic strain in the range between 0% and 15%. In this study it was observed that plastic strain occurred during the changes in elastic properties of the material, e.g., an increase in flow stress and a considerable decrease in the Young's modulus. Li *et al.* (2002) and Zang (2006) investigated the decrease of Young's modulus of aluminum alloys after plastic strain. Luo and Amit (2003) studied the springback in the DQSK steels. Placid *et al.* (2008) showed the variation in Young's modulus of TRIP 700, DP 600, HSLA 340 and AISI 304 steels. Yoshida and Uemori (2002) observed that the Young's modulus decreased with the pre-strain during a cyclic deformation and proposed an empirical expression for the Young's modulus in which some parameters should be determined by the microstructure. This empirical expression showed unfavorable to create an engineering application. Yang and Akiyama (2004) adopted both measurements macroscopic and microscopic to investigate the influence of plastic strain in the Young's modulus. Fei and Hodgson (2006) investigated the change in Young's modulus of TRIP steels under simple tension and quantified the percentage of retained austenite at each strain stage. The variation of Young's modulus and the percentage of retained austenite have been used to describe a linear equation to characterize the behavior.

In this work the objective is to analyze the consistence to measure, by nanoidentation, the Young's modulus variation related to the plastic strain.

2. EXPERIMENTAL PROCEDURE

2.1. Material

The steel type investigated in this study was the TRIP600. The thickness and chemical composition are shown in Table 1.

Table 1: Measured thickness and chemical composition range of TRIP steels

Designation	**Thickness (mm)**	**Chemical Composition (%)**				
		C	**Si**	**Mn**	**P**	**S**
TRIP	2,04	0,21 max	2,20 max	1,80 max	0,025 max	0,010 max

2.2. Methodology

The TRIP forming behavior in uniaxial strain was determined by tensile tests. An initial tensile test was made until the material rupture in order to obtain the stress-strain curve and the conventional mechanical properties. The Young's modulus was determined by means of two tests. First, the E modulus was determined through the conventional uniaxial tensile test for 0%, 2%, 4% and 8% of strain. In the second, were tested five tensile samples for each percentage of strain and the samples were sectioned in the transverse direction. This sample pieces were prepared for the microhardness measurements by the nanoidentation.

2.2.1 Tensile test

The tensile tests were performed as recommended in Australian standard AS 1391-1991 on specimens (Fig. 1) oriented along the rolling direction (Nikhare *et al.* 2008). A non-contact extensometer with a test range of 25±5mm was used. The tests were performed in a 30 kN MTS equipment. All specimens were marked by two dots, situated 25 mm apart from each other on the flat gauge section. All experiments were performed using a strain rate of $2/s^{-1}$. Different percentile of strain were investigated, 0%, 2%, 4% e 8% with six samples for each condition. Being one sample to obtain the as received material Young's modulus and five samples to determine the Young's modulus by nanoidentation method after different pre-strain.

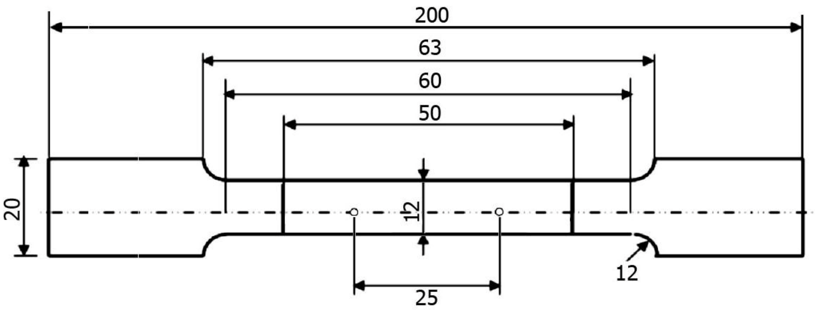
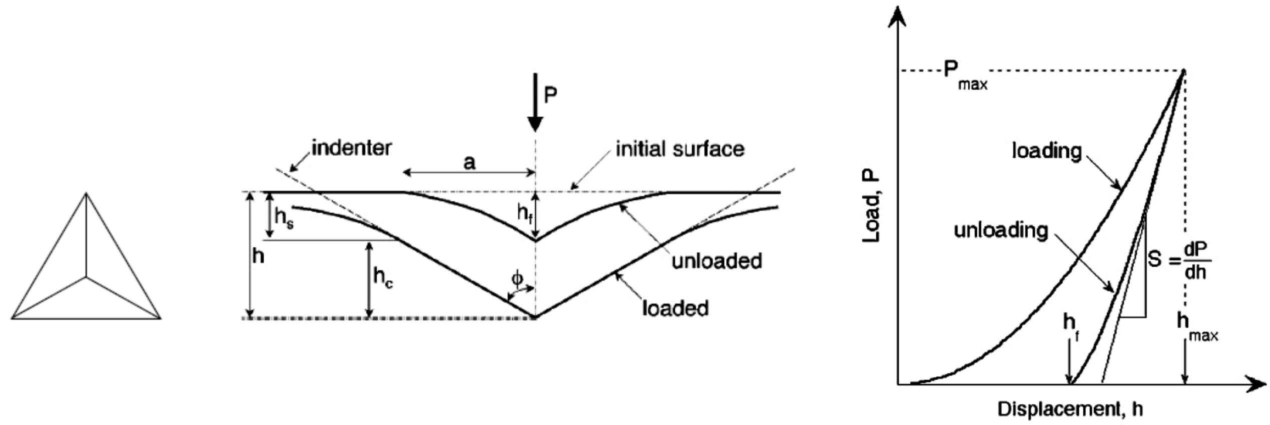


Figure 1 - Standard tensile test specimen (AS 1391-1991)

2.2.2 Micro hardness

The Young's modulus value was determined by nanoidentation on a nanoindenter equipment XP (MTS Instruments) with Berkovich indent (see Figure 2). The test was done using eight loads in each indentation with 400nN (40g). Five indentation were conducted in each one of the twenty samples. According to the method of Oliver and Pharr (1992, 2004) the Young's modulus (E) is calculated from the contact stiffness (S) which is tangent to the unloading curve (Fig. 2c) and by the projected area of contact (Ap). This area is determined from the depth of contact (Eq. 1) in the (eq.2) that makes the tip calibration. The value of Ap is replaced in (eq.3) but the result is a small value for the Young's modulus which is replaced in the equation (Eq. 4). This whole operation result in the final value for the Young's modulus.



(a) (b) (c)

Figure 2 – Nanoindentation, in (a) Berkovich indenter, in (b) schematic ilustration of the unloading process showing parameter characterizing the contact geometry, in (c) schematic ilustration of indentation load-displacement data.

$$h_c = h_t - \varepsilon \frac{F_m}{S} \tag{Eq. 1}$$

$$A_p = C_0 h_c^2 + C_1 h_c + C_2 h_c^{\frac{1}{2}} + C_3 h_c^{\frac{1}{4}} + \ldots \tag{Eq. 2}$$

$$E = \frac{\sqrt{\pi}}{2} \frac{S}{\sqrt{A_p}} \tag{Eq. 3}$$

$$\frac{1}{E} = \frac{(1-v^2)}{E} + \frac{(1-v_i^2)}{E_i} \tag{Eq. 4}$$

3. RESULTS AND DISCUSSIONS

3.1. Material

The true stress-strain curve determined in the tensile test is shown in Fig. 3. It can be observed a high value of yield strength and ultimate tensile strength. The mechanical properties obtained through the tensile test are summarized in Table 2. Where *K* is the strength coefficient and *n* is the strain hardening exponent.

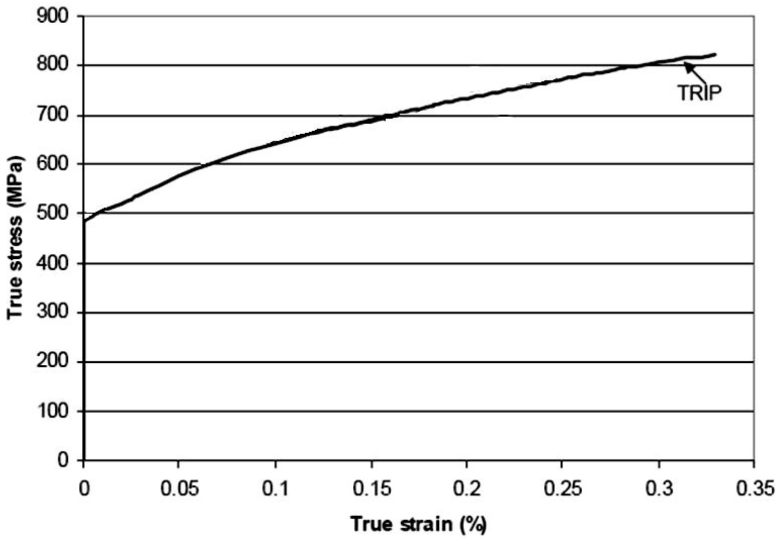


Figure 3 - True stress-strain curve determined in the tensile tests for TRIP steel

Table 2 - Mechanical properties

Steel	Yield strength (MPa)	Tensile strength (MPa)	Elongation, %	K (MPa)	n
TRIP	490	821	37	1030	0.2076

In order to obtain the modulus of elasticity by means of uniaxial tensile test, four samples were tested. It was used one sample for each percentage of strain 0%, 2%, 4% and 8%. To measure the modulus of elasticity using the nanoidentation test it was used small pieces of each one of the five uniaxial tensile samples. In each sample were produced five nanoindentations, totaling 100 nano-operations. Fig. 4 shows the average result of Young's modulus for each percentage of strain.

During nanoidentation, mainly for ductile materials, an effect called "pill-up" can occur. This effect is an elastic recovery of the region deformed by identation. This elastic recovery changes the area of identation, which consequently affects the microhardness results.

To bypass the pill-up effect an area correction was made by means of an optical microscopy. The indentation areas were corrected and the modulus of elasticity was recalculated (see Fig. 4).

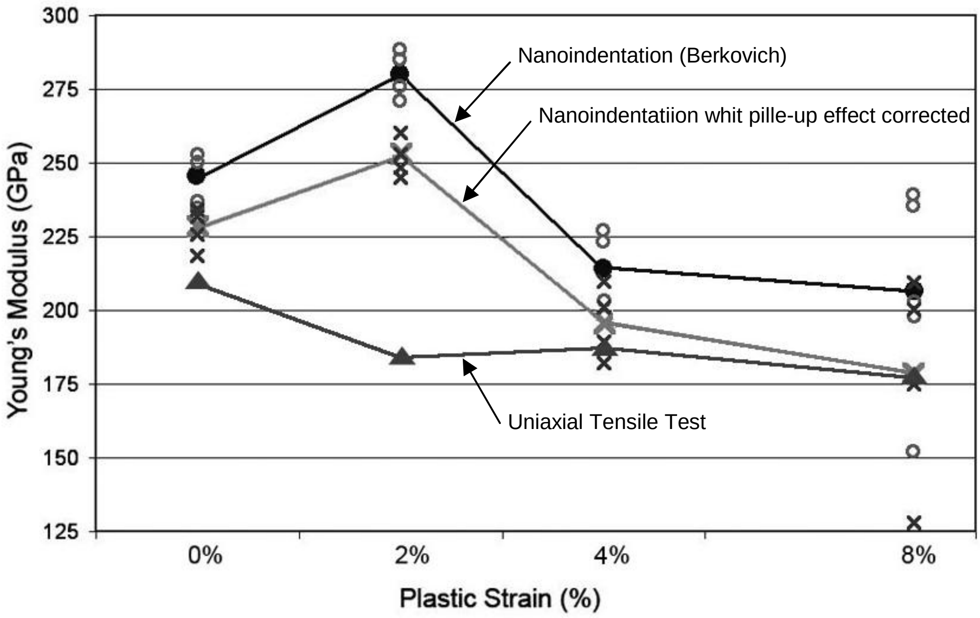


Figure 4 - Young's modulus evolution vs. plastic strain of TRIP steel.

The pill-up effect correction resulted Young’s modulus values of 10% lower than without the correction, in average, and they are more consistent compared to the results obtained by the conventional uniaxial tensile test.

As can be seen, fig. 4, the results obtained by nanoidentation for the Young’s modulus increased after 2% of strain and then decreased of a value of 15% after 4% of strain and continued decreasing to approximately 22% after 8% of strain.

The initial Young's modulus increase (for small strains) was also found in the results obtained by Morestin and Boivin (1996). In fig. 5 the authors reported a variation of the Young’s modulus for the steel XC38 (0.38% of C). The value of the initial Young modulus was 200 GPa. It increases to approximately 205 GPa after 1% of strain and reduced significantly after 2 to 3%. After 5% of strain it stabilizes at around 176 GPa (a decrease of approx. 12%). This decrease and stabilization of Young's modulus after 5% of strain led the authors to describe this behavior as two linear. One that describes the linear decrease of Young's modulus and the other the decrease observed after stabilization. The authors report that the Young's modulus evolution could be a material property that shows the bigger influence on the springback prediction.

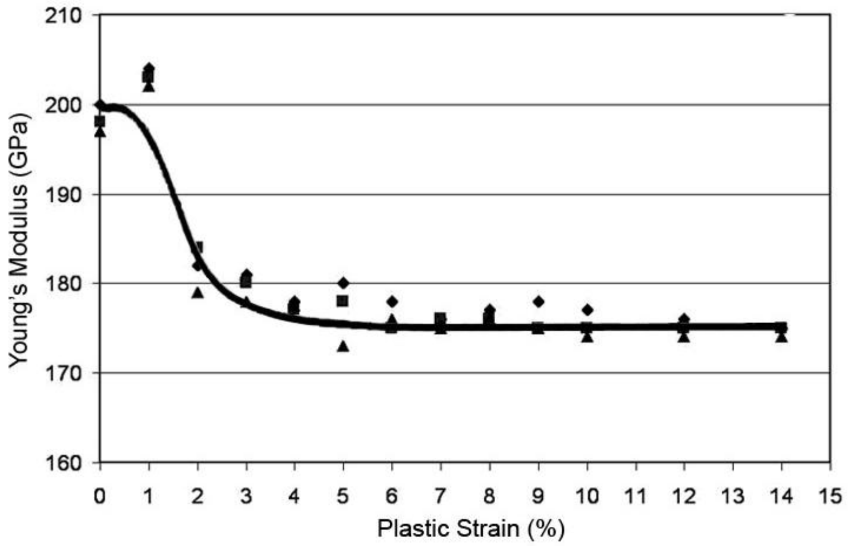


Figure 5 – Young’s modulus evolution with plastic strain. (source: Morestin and Boivin, 1996).

Fei and Hodgson (2006) described the Young's modulus decrease as just one linear trend related to plastic strain. They reported that after 20% of strain the Young’s modulus of TRIP steel (with 0.1% of C) was decreased by approximately 11% (Fig. 6). The authors, also, measured the percentage of retained austenite before and after strain and found that there was a decrease from 13 to 4%.

KULP *et al.*, (2002) reported in their study that the Young's modulus of martensite phase shows a value of 10% compared to a ferritic or austenitic matrix phase. This fact can explain, for TRIP steel, the Young’s modulus continuous decreasing with the increasing strain. Based on these results Fei and Hodgson (2006) reported this behavior as a linear equation. In fig. 6 the authors reported the results for three different thicknesses, for the same steel. We can observe that for the two finest thicknesses, between 1 and 3% of strain, the Young's modulus had values greater than the original one. The values were followed by a considerable drop from around 5% of strain. This behavior is similar to that reported by Morestin and Boivian (1996).

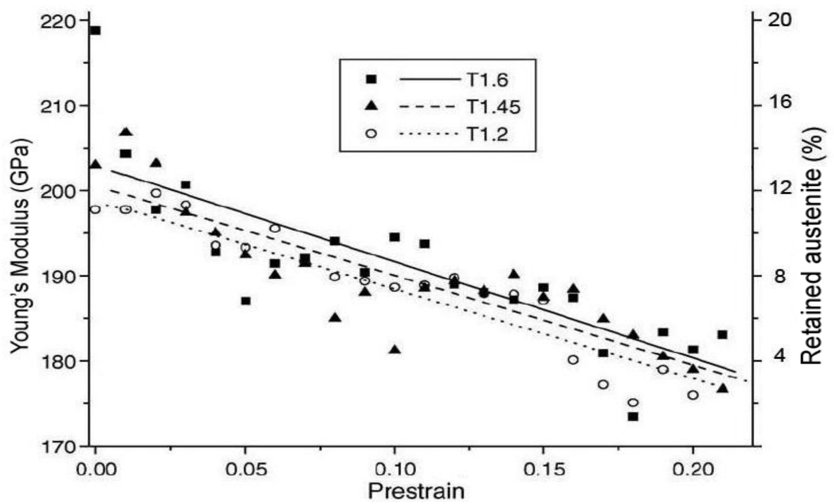


Figure 6 – Young’s modulus evolution and the percentage of retained austenite for the TRIP steel, in three different thicknesses, obtained by uniaxial tensile test. (source: Fei and Hodgson, 2006).

Yu (2009) studied the inelastic recovery behavior of TRIP steel, the effect on springback and its relationship with the Young's modulus variation. Since a variation of the elastic modulus with plastic strain was found, data points of elastic modulus vs. plastic strain were plotted in Figure 7. We can see that the elastic modulus decreased with the increase of plastic strain. Furthermore, the decrease was about 18% after 0,26 of plastic strain. Considering that the data points scattered in a regular form, a quadratic polynomial response was obtained by the regression method. The author reached the conclusion that the strain recovery during unloading process is a combination of elastic and inelastic recovery.

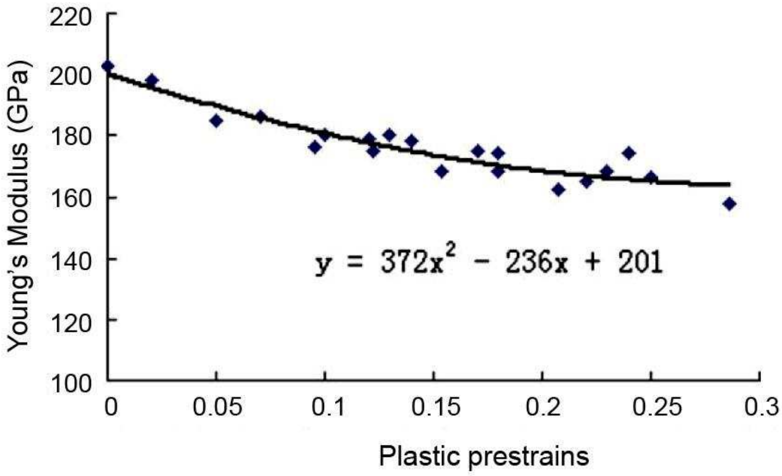


Figure 7 - Variations of elastic modulus with plastic pre-strain for TRIP600 steel.

Placid *et al.* (2008) studied the variation of Young's modulus during cyclic loading for the advanced steels. The authors showed that the Young's modulus reduction at around 2% or 3% of plastic strain can have a greatly influence on the springback response during simulation. The table 3 shows the results of Young's modulus measurements made at different grades of steel. As can be seen, there are three different values: the initial Young's modulus (E), the E value during unloading after 3% of strain (E_b) and the E value during reloading after the pre-strain (E_a).

Table 3 - Summary of results of the E-module measurements (Placid *et al.* 2008)

Material	Thickness (mm)	E (MPa)	E_a (MPa)	E_b (MPa)	Diference E_b / E
TRIP 700	1.5	205700	200900	174000	-13%
DP 600	1.5	202530	198200	177800	-12%
HSLA 340	1.5	231550	209400	185900	-20%
AISI 304	1.0	195600	191200	127500	-35%

The results showed that the E_b value after the total unloading, until the zero stress, was very different from the initial values. The reduction was more pronounced for AISI steel (-35%) while the TRIP steel showed (-13%). This value is similar to that found in this work. Fei and Hodgson (2006) showed this reduction only after 20% of strain. This difference can be credited to the different measuring procedures adopted.

The Fig.4 shows the Young's modulus results obtained by the tensile tests and nanoidentation. Despite the inconsistency at 2% of strain, the results became closer of the expect values at around 4% and converge for 8% of strain.

4. CONCLUSIONS

The young's module variation with the plastic strain of a TRIP steel was determined by uniaxial tensile test and a nanoindenter equipment. After the nanoidentation is necessary the correction of the pill-up effect and this correction can be done through the area correction obtained by an optical microscopy measurement.
After 4% of strain the material presented an E modulus decrease of 15% (in average), similar to that reported by Placid *et al.* (2008), but above the values reported by Fei and Hodgson (2006).
In general, the material investigated showed a Young's modulus decrease with the increased plastic strain. Yu (2009) showed that this decrease was due to the large plastic strain. The large plastic strain can induce bigger dislocation movements and more martensite sites, which contributed to the decrease of the elastic modulus. The behavior of this variation could not be discussed in this work and a better understanding is necessary. For this, it is necessary to do the uniaxial tensile tests for a greater number of strains, for example (0, 1, 2, 3, 4, 5, 6, 7 and 8%). The nanoidentation method proved to be a good approach for an accurate Young's modulus measurement.

5. ACKNOWLEDGMENTS

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